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IMPACT OF DARK MATTER SUBHALOS ON EXTENDED HI DISKS OF GALAXIES: POSSIBLE FORMATION OF HI FINE STRUCTURES AND STARS

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ABSTRACT

Recent observations have discovered star formation activities in the extreme outer regions of disk galaxies. However it remains unclear what physical mechanisms are responsible for triggering star formation in such low-density gaseous environments of galaxies. In order to understand the origin of these outer star-forming regions, we numerically investigate how the impact of dark matter subhalos orbiting a gas-rich disk galaxy embedded in a massive dark matter halo influences the dynamical evolution of outer HI gas disk of the galaxy. We find that if the masses of the subhalos ($M_{\rm sb}$) in a galaxy with an extended HI gas disk are as large as $10^{-3} \times M_{\rm h}$, where $M_{\rm h}$ is the total mass of the galaxy's dark halo, local fine structures can be formed in the extended HI disk. We also find that the gas densities of some apparently filamentary structures can exceed a threshold gas density for star formation and thus be likely to be converted into new stars in the outer part of the HI disk in some models with larger $M_{\rm sb}$. These results thus imply that the impact of dark matter subhalos ("dark impact") can be important for better understanding the origin of recent star formation discovered in the extreme outer regions of disk galaxies. We also suggest that characteristic morphologies of local gaseous structures formed by the dark impact can indirectly prove the existence of dark matter subhalos in galaxies. We discuss the origin of giant HI holes observed in some gas-rich galaxies (e.g., NGC 6822) in the context of the dark impact.

Subject headings: ISM:structure– (ISM:) HII regions – galaxies:ISM – galaxies:halos – galaxies:interactions

1. INTRODUCTION

Star formation activities in the extreme outer regions of gas-rich disk galaxies have recently come to be discussed extensively not only in the context of star formation laws in low-density environments of galaxies but also in the context of formation and evolution of disk galaxies (e.g., Ferguson et al. 1998a, b; Lelièvre & Roy 2000; Cuillandre et al. 2001; Martin & Kennicutt 2001; de Blok & Walter 2003; Gil de Paz et al. 2005; Thilker et al. 2005). Recent observational studies of M83 by the *Galaxy Evolution Explore (GALEX)* have discovered UV-bright stellar complexes associated with filamentary HI structures in the extreme outer disk at $R \sim 4R_{\rm HII}$, where $R_{\rm HII}$ corresponds to the radius where the majority of HII regions are detected (Thilker et al. 2005). Furthermore a number of small isolated HII regions have been recently discovered at projected distance up to 30 kpc from their nearest galaxy (e.g., NGC 1533) in the *Survey for Ionization in Neutral Gas Galaxies (SINGG)* (e.g., Meurer 2004; Ryan-Weber et al. 2003).

It has been discussed whether the observed properties of these recent star formation activities in the extreme outer HI regions of disk galaxies can be understood in terms of local gravitational instability within the HI disks (e.g., Ferguson et al. 1998a; Martin & Kennicutt 2001). Ferguson et al. (1998a) suggested that a simple picture of the local gravitational instability can not explain self-consistently the observed radial distributions of HI gas and Hα flux of star-forming regions. Star formation (proven by Hα regions) in dwarf irregular galaxies (e.g., ESO 215-G?009) with extended HI disks is observed to occur in their very outer parts, where the gas densities are well below a critical density of star formation (e.g., Warren et al. 2004). Thus it remains unclear what can control the star formation activities in the extreme outer regions of disk galaxies.

Using numerical simulations of galaxy formation based on the cold dark matter (CDM) model, Font et al. (2001) demonstrated that dark matter subhalos predicted in the CDM model can play a minor role in the heating of the disk owing to the very small number of subhalos approaching to the solar radius of 8.5 kpc. The sizes of HI disks of gas-rich galaxies are generally observed to be significantly larger than their optical disks with the sizes of $R_{\rm s}$ (Broeils & van Woerden 1994) and some fraction of low luminosity galaxies have HI gas envelopes extending out to 4–7 $R_{\rm s}$ (e.g., Hunter 1997). No theoretical attempts have been made to investigate the dynamical impact of dark matter subhalos (hereafter referred to as "dark impact" for convenience) on *the extended HI disks of galaxies*, though several numerical studies have already investigated the influences of triaxial halos with figure rotation and tidal galaxy interaction on the evolution of the extended HI disks (e.g., Theis 1999; Bekki & Freeman 2002; Masset & Bureau 2003; Bekki et al. 2005a, b).

The purpose of this Letter is to propose that the dynamical interaction between dark matter subhalos and

extended HI gas disks can be important for better understanding the origin of recent star formation observed in the extreme outer regions of disk galaxies. By using hydrodynamical simulations of the dark impact on galaxy-scale HI disks, we show that local fine structures (e.g., filaments and holes) can be formed by the dark impact in the HI disks. We discuss whether star formation can occur in high-density regions of apparently filamentary structures formed by the dark impact. We suggest that characteristic fine structures formed by the dark impact in a HI disk of a galaxy *with apparently no interacting visible dwarfs close to the disk* can indirectly prove the presence of dark matter subhalos that frequently pass through the outer part of the HI disk.

2. MODEL

We investigate how the extended HI disk of a galaxy embedded in a *fixed* dark matter halo with the total mass of $M_{\rm h}$ is dynamically influenced by a single subhalo that is orbiting the galaxy and represented by a *point mass*. In order to elucidate the essence of the dynamical effects of the dark impact more clearly, we adopt the above somewhat idealized model: We will describe the successive and cumulative impact of *numerous* subhalos with a reasonable spatial distribution within a *live* dark matter halo of a galaxy in our forthcoming papers (Bekki & Chiba 2005 in preparation). We adopt the density distribution of the NFW halo (Navarro, Frenk & White 1996) suggested from CDM simulations for the fixed dark matter halo:

$$\rho(r) = \frac{\rho_s}{(r/r_{\rm s})(1+r/r_{\rm s})^2}, \tag{1}$$

where r, ρ_s, and $r_{\rm s}$ are the spherical radius, the characteristic density of a dark halo, and the scale length of the halo, respectively. The c parameter of the NFW halo is set to be 10.0. The total baryonic mass ($M_{\rm b}$) of the galaxy is assumed to be $0.1M_{\rm h}$. Henceforth, all masses are measured in units of $M_{\rm b}$ and distances in units of $r_{\rm s}$, unless otherwise specified. Velocity and time are measured in units of $v = (GM_{\rm b}/r_{\rm s})^{1/2}$ and $t_{\rm dyn} = (r_{\rm s}^3/GM_{\rm b})^{1/2}$, respectively, where G is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_{\rm b} = 6.0 \times 10^{10}$ $M_{\odot}$ and $r_{\rm s} = 10.5\,{\rm kpc}$ as fiducial values, then $v = 1.57 \times 10^2\,{\rm km\,s^{-1}}$ and $t_{\rm dyn} = 6.55 \times 10^7$ yr.

The gas disk with the total mass of $M_{\rm g}$ is composed of 10^5 SPH (Smoothed Particle Hydrodynamics) particles and an isothermal equation of state with the sound speed of $0.02v$ is used for the gas. The gas is assumed to have an uniform radial density distribution (rather than an exponential one) and distributed for $2r_{\rm s} \le R \le 4r_{\rm s}$, because we intend to investigate the influence of the dark impact on the dynamical evolution of the outer gas disk. A reasonable dynamical model of the Galaxy embedded in the NFW halo has $r_{\rm s} \sim 0.6R_{\rm s}$, where $R_{\rm s}$ is the stellar disk size (Bekki et al 2005c). Therefore the adopted gaseous distribution corresponds to that for $1.2R_{\rm s} \le R \le 2.4R_{\rm s}$ and thus can be regarded as reasonable for investigating gas dynamics of outer HI disks of galaxies. The gas disk is assumed to be influenced only by its host dark halo (not by the inner stellar disk component), because our interests are on the evolution of the very outer part of the gas disk, where the gravitational field of its dark matter halo dominates.

The mass of the subhalo ($M_{\rm sb}$) is set to be a free parameter that can control the strength of the dark impact and ranges from $10^{-4}M_{\rm h}$ to $10^{-2}M_{\rm h}$. Although the initial position ($\mathbf{X}_{\rm sb}$) and velocity ($\mathbf{V}_{\rm sb}$) are set to be free parameters, we show the results of the models with $\mathbf{X}_{\rm sb}$ = (x,y,z) = ($3r_{\rm s}$, 0, $0.5r_{\rm s}$) and $\mathbf{V}_{\rm sb}$ = ($v_{\rm x}$,$v_{\rm y}$,$v_{\rm z}$) =(0, 0, $0.5V_{\rm c}$), where $V_{\rm c}$ is the circular velocity at $\mathbf{X}_{\rm sb}$ derived for the NFW halo. The results of other models with different $\mathbf{X}_{\rm sb}$ and $\mathbf{V}_{\rm sb}$ will be described in our forthcoming papers (Bekki & Chiba 2005). We mainly show the results of the "fiducial model" with $M_{\rm g} = 0.01M_{\rm h}$ and $M_{\rm sb} = 0.01M_{\rm h}$, which shows more clearly the roles of the dark impact in the dynamical evolution of HI gas disks in the present study. All the calculations related to the above hydrodynamical evolution have been carried out on the GRAPE board (Sugimoto et al. 1990) at the Astronomical Data Analysis Center (ADAC) at the National Astronomical Observatory of Japan. The gravitational softening parameter in the GRAPE5-SPH code (Bekki & Chiba 2005) is fixed at 0.019 in our units and the time integration of the equation of motion is performed by using the predict-corrector method with a multiple time step scheme.

3. RESULT

Figure 1 describes how gaseous fine structures are formed by the dark impact in the extended gas disk for the fiducial model with $M_{\rm sb}/M_{\rm h} = 0.01$. As the dark matter subhalo passes through the thin gas disk, it tidally disturbs the disk in a moderately strong manner. Owing to the small ratio of $M_{\rm sb}/M_{\rm h} = 0.01$, the tidal field of the subhalo is not strong enough to trigger the formation of global, non-axisymmetric structures (e.g., spiral arms and bars) and warps. The dark impact however can form local fine structures that look like "filaments" in the x-y projection and "chimneys" in the x-z projection at $T = 1.1$. As the subhalo approaches the gas disk, it gravitationally attracts gaseous particles along its path. The vertical distribution of gaseous particles close to the subhalo passing through the gas disk follows the wake induced by the subhalo. The particles consequently appear to get levitated (or lifted up) during and after the passage of the subhalo through the gas disk. Accordingly chimney-like structures can be clearly seen if the HI disk is viewed from the edge-on. These fine structures can be clearly seen in other models with $M_{\rm sb}/M_{\rm h} > 0.001$ and thus regarded as characteristics of local gaseous structures formed by the dark impact, though the details of their morphologies are appreciably different with one another.

Figure 2 shows the two-dimensional (2D) distribution of the projected gaseous densities ($\mu_{\rm g}$) of the simulated kpc-scale fine structures shown in Figure 1. Because of the tidal compression of gas by the dark impact, some parts of the structures show $\mu_{\rm g}$ higher than the threshold gas density for star formation ($\mu_{\rm thres} \sim 3{\rm M}_{\odot}$ pc^{-2}; Hunter et al. 1998). $\mu_{\rm g}$ can be as high as $\sim 14{\rm M}_{\odot}$ pc^{-2} and about 4 % of the local regions (i.e., 105 among 2500 cells) in Figure 2 have $\mu_{\rm g} > \mu_{\rm thres}$. Although we do not model star formation in the present simulations, these results imply that star formation in the extreme outer parts of gaseous disks of galaxies is highly likely to be

triggered by the dark impact.

Figure 3 shows how the strength of the dark impact controls the time evolution of $\mu_{\rm g}$ of outer gaseous disks of galaxies. The larger values of $M_{\rm sb}/M_{\rm h}$ mean that the subhalos can give stronger dynamical impact to the gas disks. It is clear from Figure 3 that (1) the maximum density of local structures formed by the stronger dark impact is higher and (2) the number fraction of cells with $\mu_{\rm g} > \mu_{\rm thres}$ is larger for the stronger dark impact. These results imply that star formation can occur in the wider regions of extended HI disks of galaxies when the HI disks are more strongly influenced by the dark matter subhalos.

The long-term evolution of local fine structures formed by the dark impact should be investigated and described in our future works with models of star formation, because star formation and its feedback (e.g., supernovae explosion) are highly likely to influence the evolution of the structures. However it would be instructive to describe some results possibly characteristic of the long-term evolution derived in the present models without star formation. Figure 4 shows the 2D distribution of $\mu_{\rm g}$ in the model with $M_{\rm sb}/M_{\rm h} = 0.001$ at $T = 6$. As shown in this figure, a kpc-scale hole surrounded by appreciably higher density regions can be finally formed as a result of the dark impact.

This result implies that without energetic thermal and kinematic feedback from massive OB stars and supernovae, giant HI holes can be formed in extended HI disks of galaxies by the dark impact. Thus the dark impact provides a new mechanism for the formation of giant HI holes observed in gas-rich dwarf irregular galaxies (e.g., LMC). The observed giant HI hole in NGC 6822 (e.g., de Blok & Walater 2003) might well be formed by dynamical impact of a very faint companion dwarf (observed as "NW cloud") on the HI disk: The physical mechanism of the HI hole formation can be essentially the same as the dark impact. Thus the HI hole in the NGC 6822 system implies the viability of the dark impact scenario of HI hole formation.

We confirm that the HI fine structures can be formed by the dark impact in models with different $M_{\rm g}$ ($< 0.05M_{\rm h}$), though the details of HI morphologies depend on $M_{\rm g}$ and initial orbits of subhalos (i.e., $\mathbf{V}_{\rm sb}$). The more remarkable chimney-like structures can be formed in the models with higher inclination of the orbits of subhalos. Apparently filamentary structures with higher gas densities can be formed by the dark impact in the model with a higher initial gas density of $M_{\rm g} = 0.02M_{\rm h}$.

4. DISCUSSIONS AND CONCLUSIONS

Although the present study has suggested that the dark impact can be responsible for star formation in the outer HI gas disks of galaxies, it remains unclear what roles the dark impact has in the evolution of HI disks *within stellar disks of galaxies.* Although the possibility of dark matter subhalos approaching galactic stellar disks is low (Font et al. 2001), we here suggest the following two possible roles of the dark impact. One is that the unique local structures of OB stars, young clusters, and super-associations, such as the galactic belt and the Gould belt in the Galaxy (e.g., Stothers & Frogel 1974), can result from the dark impact. The other is that giant HI holes without bright optical stellar counterparts (e.g., star clusters responsible for supernovae explosion that for giant HI holes) observed in some low-luminosity galaxies can be due to the dark impact. These speculative suggestions need to be investigated in a quantitatively way by our future high-resolution simulations on the dark impact on inner HI gas disks of galaxies.

The present study has shown that the previous passages of dark matter subhalos through extended HI disks of galaxies can be imprinted on fine structures (e.g., filaments and holes) in the HI disks. The present model also predicts that if a galaxy-scale halo with an extended HI gas disk has ~ 500 subhalos, ~ 8 HI fine structures can be formed by dark impact for every 1 Myr. Recent HI observations have revealed that some fraction of galaxies have very extended HI disks (e.g., Hunter 1997; Warren et al. 2004), though the total number of galaxies whose outer HI structures have been extensively investigated are very small. Accordingly we suggest that if galaxy halos are composed of numerous subhalos, as the CDM model predicts, future high-resolution HI observations on the fine structures of extended gas disks for a statistically significant number of galaxies can *indirectly* probe the existence of the subhalos and thereby provide some constraints on possible spatial distributions and kinematics of the subhalos. We also suggest that HI gas disks with apparently no interacting (visible) dwarf galaxies close to the disks would be the best observational targets for proving subhalos in galaxies.

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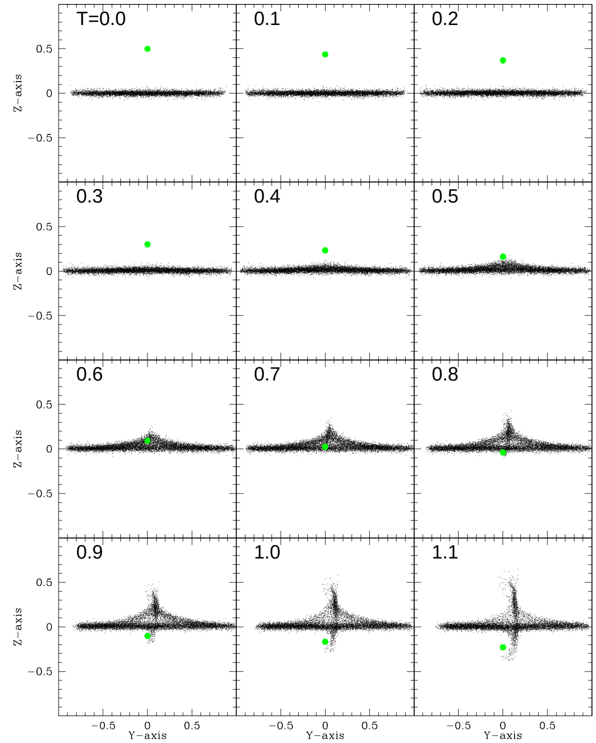

FIG. 1.— Gaseous distributions projected onto the x-z plane for the fiducial model with $M_{\rm sb}/M_{\rm h} = 0.01$. The coordinate of the center of each frame is $(x,y,z)=(x_{\rm sb},\ y_{\rm sb},\ 0)$, where $x_{\rm sb}$ and $y_{\rm sb}$ are the coordinate of the subhalo at each time step, so that the time evolution of the gas distribution influenced by the dark impact can be more clearly seen. The time T (in the simulation units) shown in the upper left corner of each panel represents time that has elapsed since the simulation starts. The position of the dark matter subhalo is shown by a green big dot. For clarity, only gas particles within $r_{\rm s}$ (=1) of the subhalo are shown.

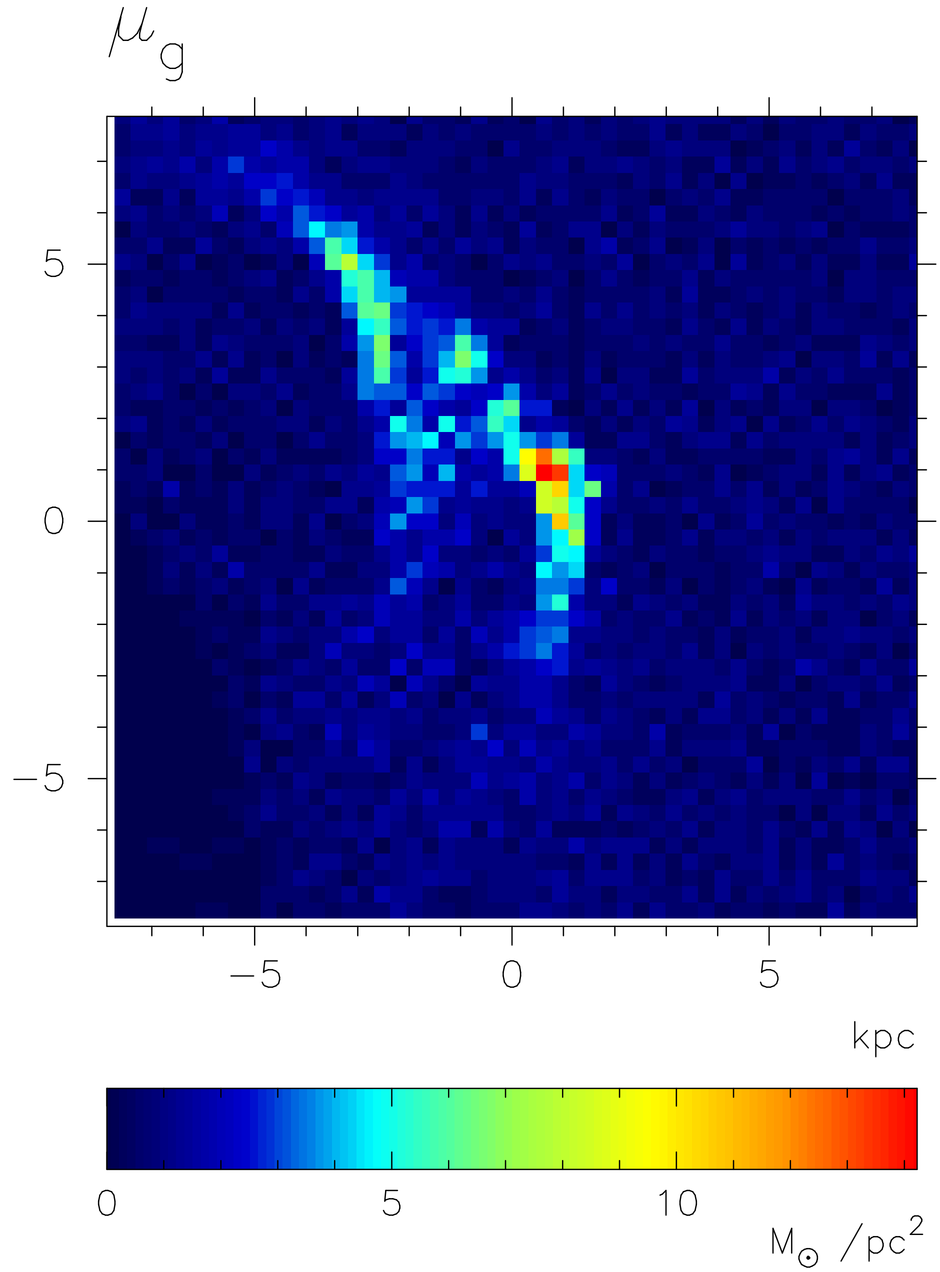

FIG. 2.— The two-dimensional (2D) gas density distributions (μ_g in units of $M_\odot$ pc^{-2}) projected onto the x-y plane for the simulated fine structures formed by the dark impact in the fiducial model at $T = 2$. For clarity, the high-density gaseous regions are set to coincide with the center of the flame. The 2D map consists of 2500 cells with the cell size of 0.315 kpc and μ_g is estimated for each cell. Note that some parts of the apparently filamentary structures exceed the threshold gas density for star formation ($\mu_{\rm thres} \sim 3 M_\odot$ pc^{-2}; Hunter et al. 1998).

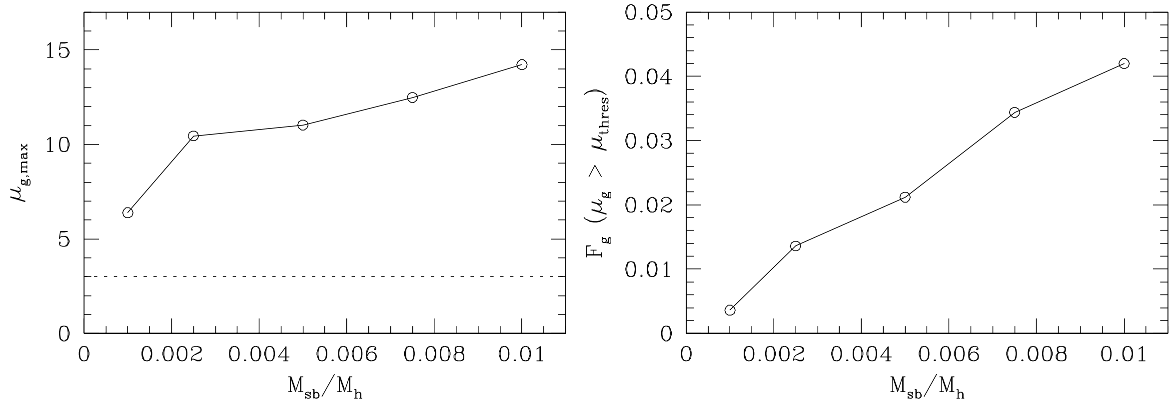

FIG. 3.— The dependences of the maximum projected gas density ($\mu_{\rm g,max}$) of the simulated fine structures (left) and the number fraction of cells ($F_{\rm g}$) with $\mu_{\rm g} > \mu_{\rm thres}$ (right) on $M_{\rm sb}/M_{\rm h}$. $\mu_{\rm thres}$ ($\sim 3{\rm M}_{\odot}$ pc^{-2}) shown by a dotted line in the left panel is the observed threshold gas density for star formation. Note that the stronger the dark impact is (i.e., the larger $M_{\rm sb}/M_{\rm h}$ is), the larger $\mu_{\rm g,max}$ and $F_{\rm g}$ are.

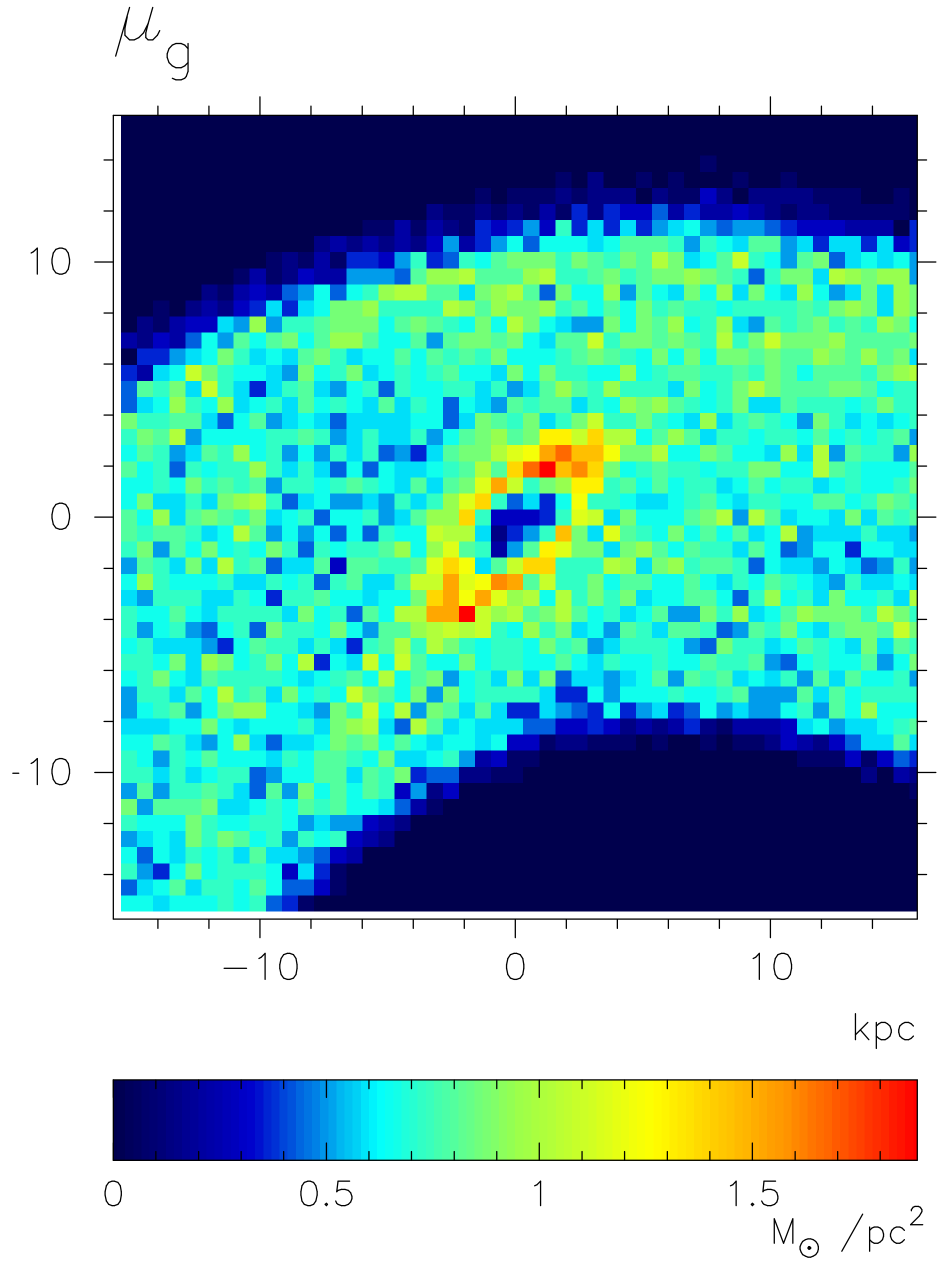

FIG. 4.— The same as Figure 2 but for the model with $M_{\rm sb}/M_{\rm h} = 0.001$ and $T = 6$. Note than a hole-like structure can be seen in the center of this frame.